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Field Effect Controlled Photoresistors Based on Chemically Deposited PbS Films

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ABSTRACT

MOS-like structures were obtained by chemical deposition of a polycrystalline PbS thin film on top of a silicon dioxide/Si substrate. Gold ohmic electrodes in coplanar configuration were subsequently deposited by vacuum evaporation on PbS surface (drain and source electrodes). The gate aluminum electrode was deposited on the back of the Si substrate. The dependence of the photoconductive signal, generated in the PbS film, on the gate voltage was studied for wavelengths ranging between 800 nm and 3000 nm at room temperature as well as at low temperatures. It was found that the relative variation of the signal could be as high as 50 % for gate voltages ranging between -30 V and +30 V. Two possible mechanisms are proposed to explain the signal variation with the gate voltage: 1) Variation of the depleted region's thickness in the PbS film, that leads to a variation of the conduction channel's resistance (the reference resistance called, also, the dark resistance), 2) The possible variation of the majority carriers (holes) life-time due to the electron blocking at the PbS/oxide interface when positive gate voltages are applied on the back electrode. Integrated IR detectors with controlled sensitivity in the 800-3000 nm range can be manufactured at a relatively low cost using the PbS/oxide/Si MOS-like structure.

INTRODUCTION

Lead sulfide (PbS) is a A_4B_6 semiconductor compound with very good photoconductive properties in the near infrared (NIR) spectrum. The sensitivity domain at room temperature is 600-3000 nm, with a maxima at around 2200-2400 nm [1,2]. The standard method used to obtain PbS thin films with good IR detection properties is the Chemical Bath Deposition (CBD) [3-5]. Other technique that started to be used in the last years for producing PbS based optoelectronic devices (laser diodes) is the hot wall epitaxy [6].

PbS films are mainly used to produce high sensitivity photoconductive cells for NIR. The spectral sensitivity could be as high as $10^{11} \text{ cm}^2 \text{ W}^{-1} \text{ Hz}^{-1/2}$ at maximum wavelength [7]. Even PbS was intensively studied in the past, being considered as the template of polycrystalline semiconductor compounds, further studies are under way on this material in the last years. The main target of these are: 1) to clarify the connection between bath composition, film morphology and physical properties of the film [3,8-10]; 2) to integrate PbS IR detectors with standard semiconductor technology [11,12]; 3) to develop new types of heterojunctions and heterostructures with enhanced detection properties by combining PbS with other materials (semiconductors or/and dielectrics) [11-13]. The last direction of research is particularly interesting because offers the possibility to manufacture different type of devices, including field effect ones [14].

The paper continues the study of field effect assisted photoconductivity started in our group in the last 5 years [14,15]. It presents an enhanced PbS based heterostructure, obtained by deposition of

a PbS layer on a SiO_2/Si (n-type) substrate. A MOS-like structure was manufactured and the influence of the field effect on the photoconductive properties of PbS film were investigated.

EXPERIMENTAL DETAILS

The SiO_2 layer was grown on single crystalline n-type Si wafers. The thermal oxidation in oxygen and water vapors at 850°C was used. The final thickness of the SiO_2 layer was of about 250 nm. The PbS film was deposited by CBD method, using lead nitrate ($\text{Pb}(\text{NO}_3)_2$) as Pb^{2+} ions source and thiourea as S^{2-} ions source. The deposition is performed in alkaline medium, using sodium hydroxide (NaOH), the starting solution pH being 11. Small amounts of a reducing agent (hydroxylamine chlorhydrate) and of a Bi salt are introduced in the bath in order to control the nucleation/growth process during the deposition of the PbS layer. The PbS film is then photolithographic processed, leaving an area of $2.5 \times 3.5 \text{ mm}^2$. Gold electrodes are vacuum evaporated on PbS surface, the final active area being of $1.5 \times 1.5 \text{ mm}^2$. After electrode deposition, the PbS films are aged at 80°C for about 80 hours, in air. The final structure is schematically presented in fig. 1, together with the electric set-up used for field effect assisted photoconductivity measurements.

The sample was introduced in the closed-cycle He cryostat with IR optic facilities and the measurements were performed in modulated light, using the standard set-up composed by a grating monochromator model Spex270, a lock-in amplifier model SR830DSP, a d.c. voltage source (2 channels) model Grundig 300, an incandescent lamp as an IR source (30 W nominal electric power) and a mechanical chopper model Ithaco 383A. The value of the load resistance was 500 kohm.

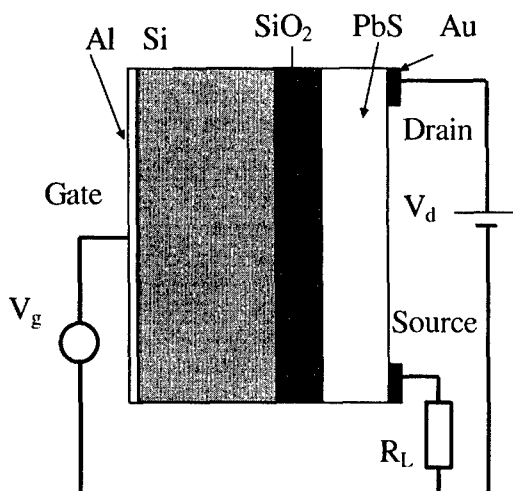


Fig. 1 The schematic of the pseudo-MOS $\text{PbS}/\text{SiO}_2/\text{Si}$ structure and of the electrical set-up used for field effect assisted photoconductivity measurements. V_d – drain voltage; V_g – gate voltage; R_L – load resistance.

RESULTS AND DISCUSSION

In fig. 2 the spectral distribution of responsivity, for different polarities and values of the gate voltage, are presented. The responsivity is defined as the ratio between the measured signal S , expressed in Volts (V), and the incident power P_{inc} on the detector surface, expressed in Watts (W):

$$R(V/W) = \frac{S(V)}{P_{inc}(W)} \tag{1}$$

The drain voltage was in all cases +30 V. The open square curve was obtained for floating gate (the gate electrode is not connected). It can be observed that for positive gate voltages the signal increases and for negative gate voltages decreases on the entire sensitivity range of PbS. We remind that, for photoconductive measurements, a d.c. voltage is applied on the drain electrode while the signal is collected from the load resistance connected to the source electrode.

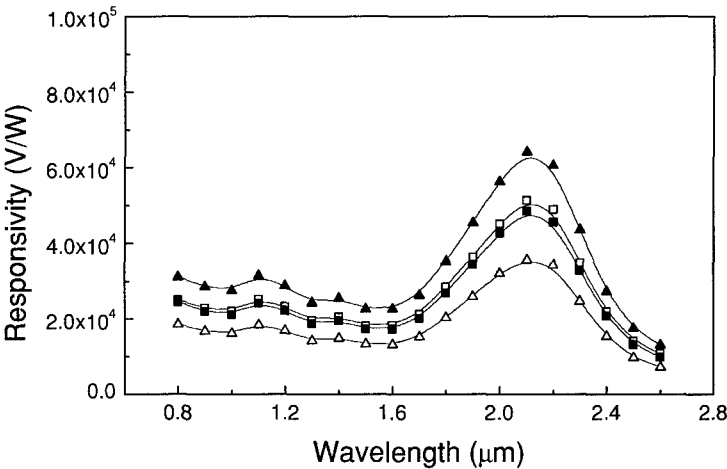


Fig. 2 Spectral distribution of responsivity in case of PbS/SiO₂/Si heterostructures, for different gate voltages. Open squares-floating gate; Solid squares-ground gate; Solid triangles- $V_g=+30$ V; Open triangles- $V_g=-30$ V. Drain voltage was +30 V.

The wavelength was then set to a certain value (1000 nm and 2000 nm) and the room temperature dependence of the photoconductive signal on the gate voltage was raised. The obtained results are presented in fig. 3. The dependence is almost linear up to about $V_g = 15$ V and then has the tendency to saturate. Finally, the temperature dependence of the photoconductive signal was raised for different gate voltages (see fig. 4).

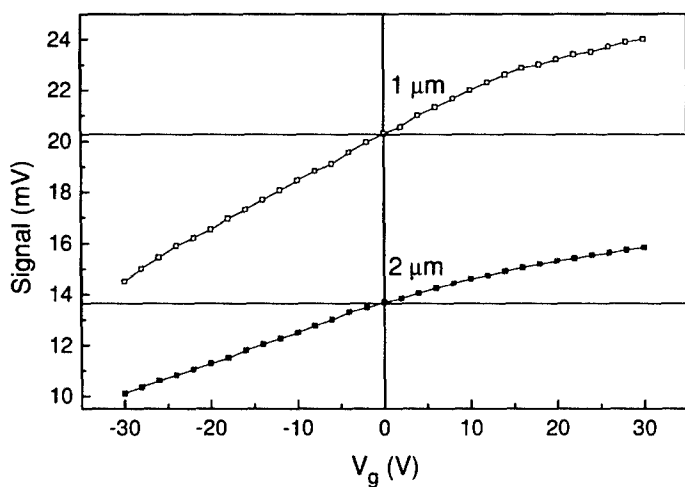


Fig. 3 The dependence of the photoconductive signal on the gate voltage.

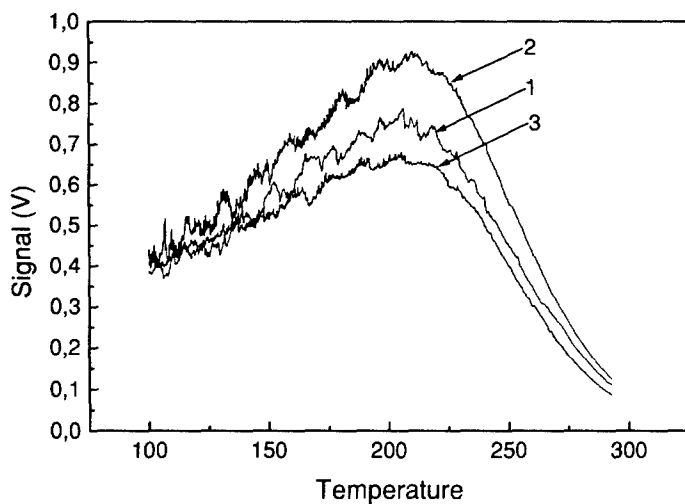


Fig. 4 The temperature dependence of the photoconductive signal, determined for different gate voltage: 1) 0 V gate voltage; 2) +30 V gate voltage; 3) -30 V gate voltage. The drain voltage was +30 V in all cases. The light was collimated on the transparent IR window of the cryostat.

From fig. 2,3 and 4 it can be seen that the photoconductive signal increases for positive gate voltage and decreases for negative ones, no matter the wavelength and temperature (at least in the 150-300 K domain). This behaviour can be explained if the influence of the field effect on the photoconductivity of PbS film is taken into consideration. The field effect is favoured by the existence of the thin SiO₂ layer that is present between the two semiconducting materials. There are two ways by which the gate voltage can change the photoconductive signal:

- a) Changing the apparent „thickness“ of the PbS film. When the gate is positive the two interfaces (PbS/SiO₂ and SiO₂/Si) go to depletion. In this case the PbS layer can be regarded as being composed of 2 distinct layers: the depleted layer, that has no free charges and, thus, no current is flowing through it; the surface conductive layer. When increasing the gate voltage V_g, the thickness of the depleted layer increases and that of the conductive layer decreases. These changes lead to an increase of photoconductive signal according with the formula:

$$\Delta v = \frac{R_L V_d}{(R_L + \frac{\rho}{d - x_{PbS}})^2} \frac{\Delta \sigma}{\sigma^2} \frac{1}{d - x'_{PbS}} \quad (2)$$

where: where: $\Delta \sigma$ is the electric conductivity variation of PbS film when it is exposed to light; σ is the dark electric conductivity of PbS film; x_{PbS} is the thickness of space charge region in PbS in dark condition; x'_{PbS} is the thickness of the space charge region in PbS when the film is exposed to light; ρ is the resistivity of the PbS film; V_d is the drain voltage; d is the total thickness of the PbS film. The quantities x_{PbS} and x'_{PbS} will depend on the gate voltage [16] (will increase with increasing V_g). x'_{PbS} will depend also on the concentration of the photogenerated carriers, as well as $\Delta \sigma$. Anyway, the dependence of the photoconductive signal on the gate voltage will be similar with that presented in fig. 3.

- b) Changing the carriers life-time. When positive gate voltage is applied electrons will be attracted to the PbS/SiO₂ interface, thus the photogenerated holes life-time will increase and same will do the photoconductive signal, according with the following formula [17]:

$$I_{foto} = q(\eta \frac{P_{opt}}{h\nu}) (\frac{\mu_n \tau E}{L}) \quad (3)$$

where: η is the quantum efficiency; P_{opt} is the incident optical power; $h\nu$ is the energy of the incident light; μ_n is the carrier mobility (holes in this case); τ is the life-time; E is the longitudinal applied electric field; L is the distance between coplanar electrodes from the surface of PbS film. If the gate voltage is negative then holes will be attracted at the PbS/SiO₂ interface. Thus the electron concentration in the conductive channel will increase, the recombination probability will be higher and the life-time of photogenerated holes will decrease, leading to a smaller photoconductive signal.

In our opinion the first mechanism is dominant for relatively small gate voltages, may be up to 10 or 15 V. After that, some inversion can occur at the PbS/SiO₂ interface. In this case, further increasing of the gate voltage will have little effect on the photoconductive signal because the negative charge accumulated at the PbS/SiO₂ interface will not allow other electrons to be attracted there. This could explain why with increasing the positive gate voltage the signal has the tendency to saturate.

CONCLUSIONS

A pseudo-MOS structure was developed on the basis of a PbS/SiO₂/Si heterostructure. It was both experimentally and theoretically shown that the photoconductive signal can be controlled by field effect. On a wide range of wavelengths and temperatures the signal variation can be as high as 50 %. From the detection point of view the most important thing is that the photoconductive signal can be increased with almost 25% if positive gate voltages are applied on the structure.

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